Technical Report Documentation Page

1. REPORT No.
FHWA/CA/TL-86/12

2. GOVERNMENT ACCESSION No.

3. RECIPIENT'S CATALOG No.

4. TITLE AND SUBTITLE
The Construction and Initial Evaluation of a Sulfur Extended Asphalt (SEA) Pavement in a Cold Climate

5. REPORT DATE
October 1986

6. PERFORMING ORGANIZATION

7. AUTHOR(S)
N.H. Predoehl

8. PERFORMING ORGANIZATION REPORT No.
54324-633354

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Office of Transportation Laboratory
California Department of Transportation
Sacramento, California 95819

10. WORK UNIT No.

11. CONTRACT OR GRANT No.
F81TL05

12. SPONSORING AGENCY NAME AND ADDRESS
California Department of Transportation
Sacramento, California 95807

13. TYPE OF REPORT & PERIOD COVERED
Interim II- 1984-1986

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES
This study was performed in cooperation with the U.S. Department of Transportation, Federal Highway Administration, as part of the research project entitled: "An Evaluation of Sulfur Extended Asphalt (SEA) Pavements in Cold and Hot Climates".

16. ABSTRACT
Caltrans placed its second SEA test section at a cold weather site on U.S. 6 (Road 09-Mno-6-18.2/26.4) about 30 miles north of Bishop, California, at Benton, California. The test sections, varying from 1100 to 2200 ft, included an AR-2000 control and SEA 20% and 40% sections which were placed as part of a rehabilitation and overlay job from May 30 thru June 4, 1984. Reported are details of the design, installation and first year evaluation. The SEA was mixed in the pugmill after weighing, with no preblending apparatus. Paving involved conventional procedures and equipment. Initial findings reveal no unusual problems as a result of SEA regarding mix design, mixing temperature control, paving compaction, and environmental controls. Laboratory and field test on the mixes, binders, and test sections reveal similar results. Tests on cores removed 11 months after construction revealed only slight weathering changes in all sections. Condition and crack surveys before and 16 months after construction show significant reflection cracking in the SEA 40% sections, primarily in the northbound lane (42.5%) and some longitudinal and block cracking in the AR -2000 control section.

17. KEYWORDS
Sulfur Entended Asphalt (SEA) sulfur, pugmill blending/mixing of SEA, cold weather SEA test section

18. No. OF PAGES:
74

19. DRI WEBSITE LINK
http://www.dot.ca.gov/hq/research/researchreports/1981-1988/86-12.pdf

20. FILE NAME
86-12.pdf

STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION
DIVISION OF FACILITIES CONSTRUCTION
OFFICE OF TRANSPORTATION LABORATORY

THE CONSTRUCTION AND INITIAL EVALUATION OF A SULFUR EXTENDED ASPHALT (SEA) PAVEMENT IN A COLD CLIMATE (INTERIM REPORT II)

Study Supervised by .... R. N. Doty, P.E.

Principal Investigator .... G. R. Kemp, P.E.

Co-Investigators .... N. H. Predoehl
.... R. Reese, P.E.

Report Prepared by .... N. H. Predoehl

R. A. FORSYTH, P.E.
Chief, Office of Transportation Laboratory

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
FHWA/CA/TL-86/12		

4. TITLE AND SUBTITLE
The Construction and Initial Evaluation of a Sulfur Extended Asphalt (SEA) Pavement in a Cold Climate

5. REPORT DATE
October, 1986

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
N. H. Predoehl

8. PERFORMING ORGANIZATION REPORT NO.
54324-633354

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Office of Transportation Laboratory
California Department of Transportation
Sacramento, California 95819

10. WORK UNIT NO.

11. CONTRACT OR GRANT NO.
F81TL05

12. SPONSORING AGENCY NAME AND ADDRESS
California Department of Transportation
Sacramento, California 95807

13. TYPE OF REPORT & PERIOD COVERED
Interim II - 1984-1986

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES This study was performed in cooperation with the U.S. Department of Transportation, Federal Highway Administration, as part of the research project entitled: "An Evaluation of Sulfur Extended Asphalt (SEA) Pavements in Cold and Hot Climates".

16. ABSTRACT

Caltrans placed its second SEA test section at a cold weather site on U.S. 6 (Road 09-Mno-6-18.2/26.4) about 30 miles north of Bishop, California, at Benton, California. The test sections, varying from 1100 to 2200 ft, included an AR-2000 control and SEA 20% and 40% sections which were placed as part of a rehabilitation and overlay job from May 30 thru June 4, 1984. Reported are details of the design, installation and first year evaluation. The SEA was mixed in the pugmill after weighing, with no preblending apparatus. Paving involved conventional procedures and equipment. Initial findings reveal no unusual problems as a result of SEA regarding mix design, mixing temperature control, paving, compaction, and environmental controls. Laboratory and field test on the mixes, binders, and test sections reveal similar results. Tests on cores removed 11 months after construction revealed only slight weathering changes in all sections. Condition and crack surveys before and 16 months after construction show significant reflection cracking in the SEA 40% sections, primarily in the northbound lane (42.5%) and some longitudinal and block cracking in the AR-2000 control section.

17. KEY WORDS	18. DISTRIBUTION STATEMENT
Sulfur Entended Asphalt (SEA) sulfur, pugmill blending/mixing of SEA, cold weather SEA test section	No Restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

19. SECURITY CLASSIF. (OF THIS REPORT)	20. SECURITY CLASSIF. (OF THIS PAGE)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified		

DS-TL-1242 (Rev.6/76)

CONVERSION FACTORS

English to Metric System (SI) of Measurement

Quantity	English unit	Multiply by	To get metric equivalent
Length	inches (in)or(")	25.40 .02540	millimetres (mmm) metres (m)
	feet (ft)or(')	.3048	metres (m)
	miles (mi)	1.609	kilometres (km)
Area	square inches (in^2)	6.432×10^{-4}	square metres (m^2)
	square feet (ft^2) acres	.09290 .4047	square metres (m^2) hectares (ha)
Volume	gallons (gal)	3.785	litres (l)
	cubic feet (ft^3)	.02832	cubic metres (m^3)
	cubic yards (yd^3)	.7646	cubic metres (m^3)
Volume/Time (Flow)	cubic feet per second (ft^3/s)	28.317	litres per second (l/s)
	gallons per minute (gal/min)	.06309	litres per second (l/s)
Mass	pounds (lb)	.4536	kilograms (kg)
Velocity	miles per hour (mph) feet per second (fps)	.4470 .3048	metres per second (m/s) metres per second (m/s)
Acceleration	feet per second squared (ft/s^2)	.3048	metres per second squared (m/s^2)
	acceleration due to force of gravity (G)	9.807	metres per second squared (m/s^2)
Weight Density	pounds per cubic (lb/ft^3)	16.02	kilograms per cubic metre (kg/m^3)
Force	pounds (lbs) kips (1000 lbs)	4.448 4448	newtons (N) newtons (N)
Thermal Energy	British thermal unit (BTU)	1055	joules (J)
Mechanical Energy	foot-pounds (ft-lb) foot-kips (ft-k)	1.356 1356	joules (J) joules (J)
Bending Moment or Torque	inch-pounds (ft-lbs) foot-pounds (ft-lbs)	.1130 1.356	newton-metres (Nm) newton-metres (Nm)
Pressure	pounds per square inch (psi)	6895	pascals (Pa)
	pounds per square foot (psf)	47.88	pascals (Pa)
Stress Intensity	kips per square inch square root inch (ksi $\sqrt{in}$)	1.0988	mega pascals $\sqrt{metre}$ (MPa $\sqrt{m}$)
	pounds per square inch square root inch (psi $\sqrt{in}$)	1.0988	kilo pascals $\sqrt{metre}$ (KPa $\sqrt{m}$)
Plane Angle	degrees (°)	0.0175	radians (rad)
Temperature	degrees fahrenheit (F)	$\frac{tF - 32}{1.8} = tC$	degrees celsius (°C)

ACKNOWLEDGEMENTS

This is to acknowledge the efforts of many individuals who assisted in the gathering of data for this report. Special recognition is given to Hideyo Hashimoto, Kenneth Iwasaki, and Ronald Morrison who participated in the mix design and materials testing. Recognition is also given to Dawn Becky, Gene Stucky, Burt Anderson, and Jay Abegglen for performing the coring and field testing. Appreciation is also extended to those involved with the typing and editing of this report - Kennie Callahan and Eileen Howe.

NOTICE

The contents of this report reflect the views of the Office of Transportation Laboratory which is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Neither the State of California nor the United States Government endorse products or manufacturers. Trade or manufacturers' names appear herein only because they are considered essential to the object of this document.

TABLE OF CONTENTS

TABLE OF CONTENTS (Con't)

FIGURES

TABLES

TABLES (Con'T)

INTRODUCTION

Since 1981, the California Department of Transportation (Caltrans) Laboratory (TransLab) in Sacramento has been conducting an FHWA-sponsored research study of sulfur extended asphalt (SEA). The study plan of the research project proposed two field test sections, one hot climate and one cold climate, in which to pursue the study objectives which are:

1. Determine whether one grade of soft asphalt can be used in both cold and hot areas with the addition of sulfur to change the characteristics of the resulting mixture so that the needs of both climates could be met with one soft asphalt product.

2. Determine the durability of the resulting SEA pavement in each environment.

3. Develop laboratory test procedures which will predict SEA mixture field performance.

The hot climate test section (Baker Test Section) was placed on I-15 (Road 08-SBd-15-107.15/110.0) in San Bernardino County between Baker and Barstow, California, in September, 1982. (1)

This report details the planning, installation, and first year evaluation of the cold climate SEA test section (Benton Test Section) located on US-6 (Road 09-Mno-6-18.2/26.4) about 30 miles north of Bishop, California, that was placed May 30 to June 4, 1984.

As in the Baker Test Section, two SEA blends, 20 and 40 percent*, plus the blending AR-2000 asphalt were used in this test section. The job asphalt was also AR-2000. This SEA operation differed from the Baker Test Section in that the asphalt and sulfur were not preblended prior to adding to the pugmill. Instead, they were blended during the mixing phase.

*All sulfur percentages indicated in the text are "by weight" of total binder.

FINDINGS AND CONCLUSIONS

Since this report concerns the planning, installation, and first year evaluation of the cold climate SEA test sections, the findings and conclusions will encompass those areas.

1. No new problems arose in the design of SEA mixes for the Benton Test Section. As in the preparation for the Baker Test Section, compensation for the specific gravity of sulfur was the only difference from designing a regular asphalt mix.

2. Injection and blending of the asphalt and sulfur in the weigh bucket and pugmill produced a well blended SEA mix. This method of asphalt-sulfur blending appears to be a viable and successful way of producing an SEA mix.

3. Although the blending of asphalt and sulfur in the weight bucket and pugmill is practical and successful, it does not allow for sampling of the blended asphalt-sulfur; thus, testing to determine the percent sulfur in the binder is not possible. This makes it imperative that weigh-bucket controls are in excellent working order.

4. Nuclear density results of the finished sections show that the SEA 40% section had the highest relative compaction of the three different sections, duplicating the compaction results of the Baker Test Section (1). Evidently the greater percentage of sulfur causes a slower

rate of cooling in the mix, which promotes better compaction of the pavement.

5. As in the Baker Test Section(1) installation, compliance with the OSHA regulations for H_2S and SO_2 emissions was no problem in the work areas due to good temperature control of the hot plant.

6. Particulate (nuisance dust) levels were very responsive to wind conditions at the plant and, to a lesser extent, on the street. If strong winds are prevalent, excessive dust can result. Free sulfur levels were highest on the street during the SEA paving operation as expected.

7. With the use of the hot extraction test (California Test 310), it was again(1) possible to obtain an accurate determination of the weight percent binder in the SEA mixes. Test results on samples from the windrow indicate excellent adherence to design recommendations.

8. Results of tests on cores after the moisture vapor susceptibility procedure appear to indicate that SEA mixes have greater resistance to moisture susceptibility than regular asphalt mixes.

9. Test results on recovered binders from mix samples taken from the windrow show that the sulfur causes a reduction in viscosity of the binder in the fresh mix. This duplicates the viscosity pattern of the Baker Test Section and of laboratory mixed SEA binders.

10. The determination of the sulfur content of the recovered residues again verifies the experiments of Kennepohl-(2) which indicated that approximately 20 percent sulfur goes into solution with the asphalt by weight of the total binder.

11. Prediction of SEA binder durability (control and SEA 40% similar - SEA 20% worse) using the California Tilt Oven Durability (CATOD) test on blended SEA samples from the Benton Test Section follows a pattern similar to that for the Baker Test Section. These predictions will require confirmation by field performance.

12. Field testing of the Benton Test Section shows a generally well constructed and uniform test section.

13. Significant reflection cracking of transverse cracks in the SEA 40% northbound lane (42.5%) and southbound lane (12.1%) was revealed by crack and condition surveys conducted prior to and 16 months after test section installation. Only minor cracking is evident in the SEA 20% and control lanes.

14. Core samples removed 11 months after construction revealed that the southbound lane (0.25 ft average pavement thickness) was approximately 0.10 ft thicker than the northbound lane (0.16 ft average). The design thickness was 0.15 ft. This difference in the thickness could explin the greater incidence of cracking in the northbound lane. (See previous finding No. 13).

15. Data generated by tests on whole cores and recovered binders (cored 11 months after construction) show no significant changes in properties other than normal slight hardening of each binder.

IMPLEMENTATION

This report summarizes the construction and early evaluation of the use of SEA in a cold climate. Early results seem to indicate that SEA mixtures with sulfur contents greater than the amount which will go into solution (greater than 20% by weight) may be more brittle in colder climates. This possibility should make the use of high sulfur percentage SEA mixtures in colder climates questionable.

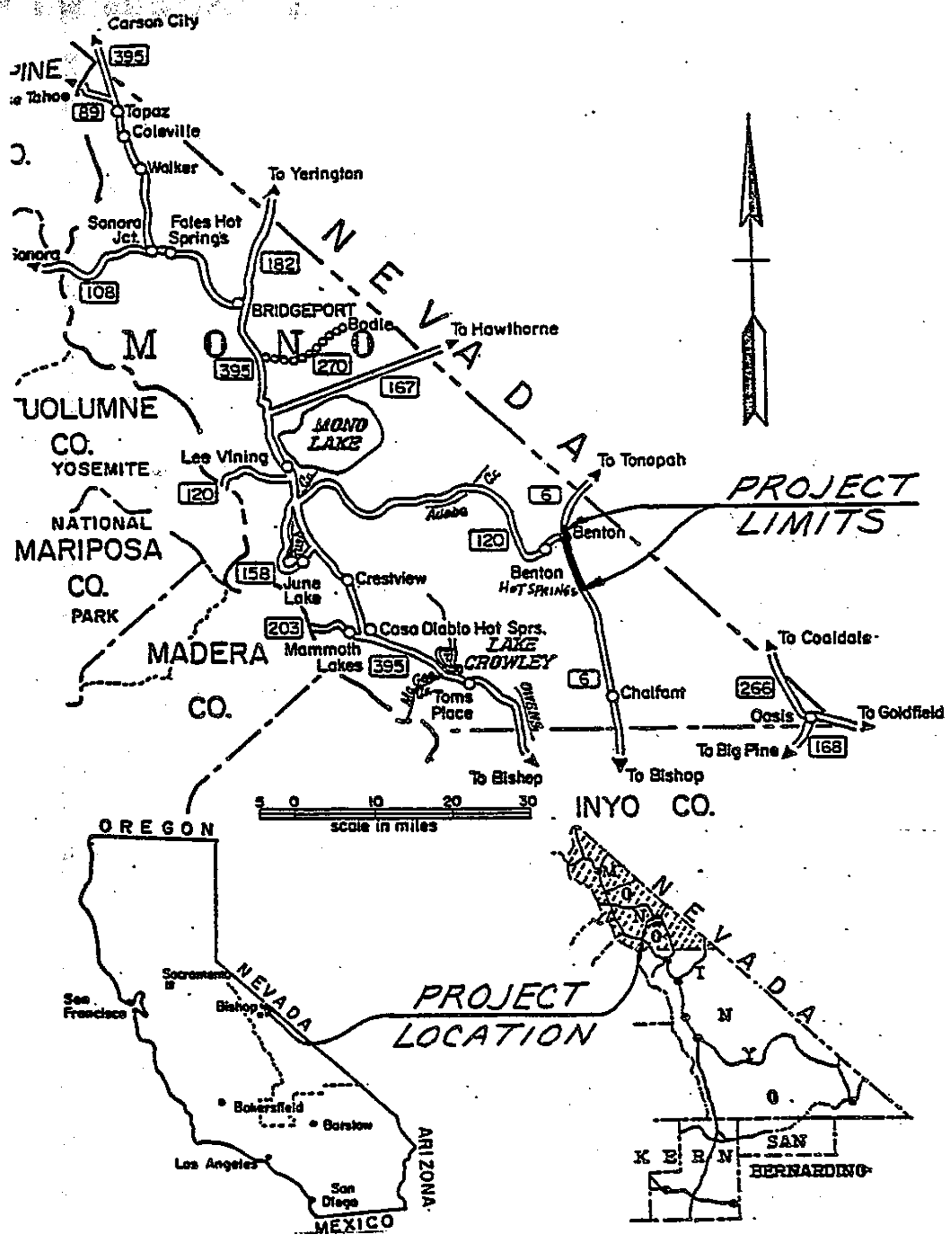
TEST SECTION

I. Location

The cold climate SEA test section was designed as a 0.15' overlay on an overlay and reconstruction job (Contract 09-071004) in the northbound and southbound lanes of U.S. 6 in the town of Benton, California. This roadway is in a high desert valley between mountain ranges near the California-Nevada border. The elevation of the test section location is approximately 5350 feet above sea level. The test section is virtually flat with about a one percent grade increase from south to north. Winters are cold but with minimal snow. The route is the main all-weather route between Los Angeles and Reno. Figures 1 and 2 show the geographical location and details of the test section.

II. Existing Roadbed Condition

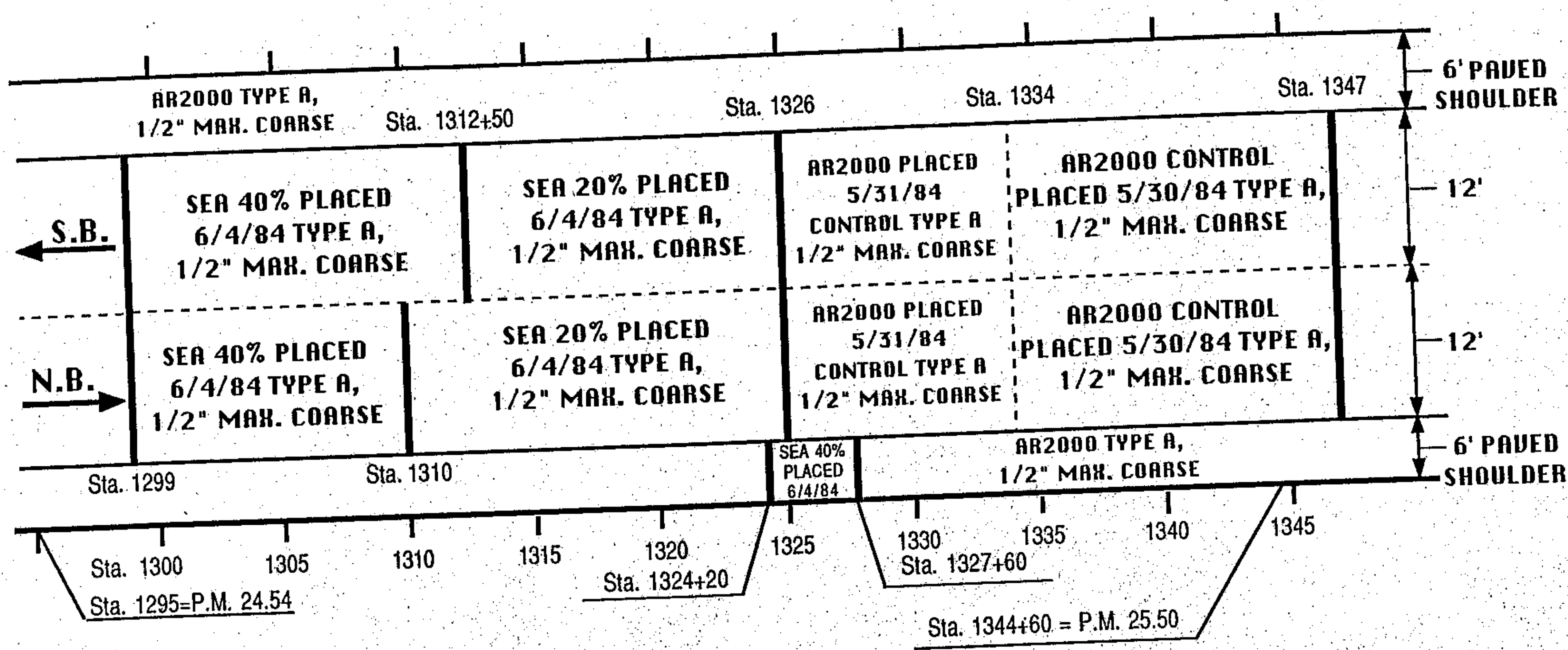
The portion of the roadbed used for the test section had 0.25 ft AC surfacing over 0.50 ft of imported borrow. The most recent paving had been a 0.08 ft AC overlay placed in 1977. The road was extensively cracked with longitudinal, transverse, and alligator cracking in the wheel paths (see Figure 3). Deflection data obtained in 1980 indicated mean deflections of 0.014 in. in both the northbound and southbound lanes and 80th percentile values of 0.018 in. in the southbound lane and 0.019 in. in the northbound lane. Traffic volumes reported in the District 9 project report indicated a 1979 ADT of 1900 with 15 percent trucks. The 1995 ADT is estimated to be 2500. This is for two-way traffic on this two-lane road.



BENTON TEST SECTION

Location Map

Figure 1



LAYOUT OF TEST SECTIONS
BENTON, CA - ROAD 09-MNO-6-18.2/26.4

Figure 2

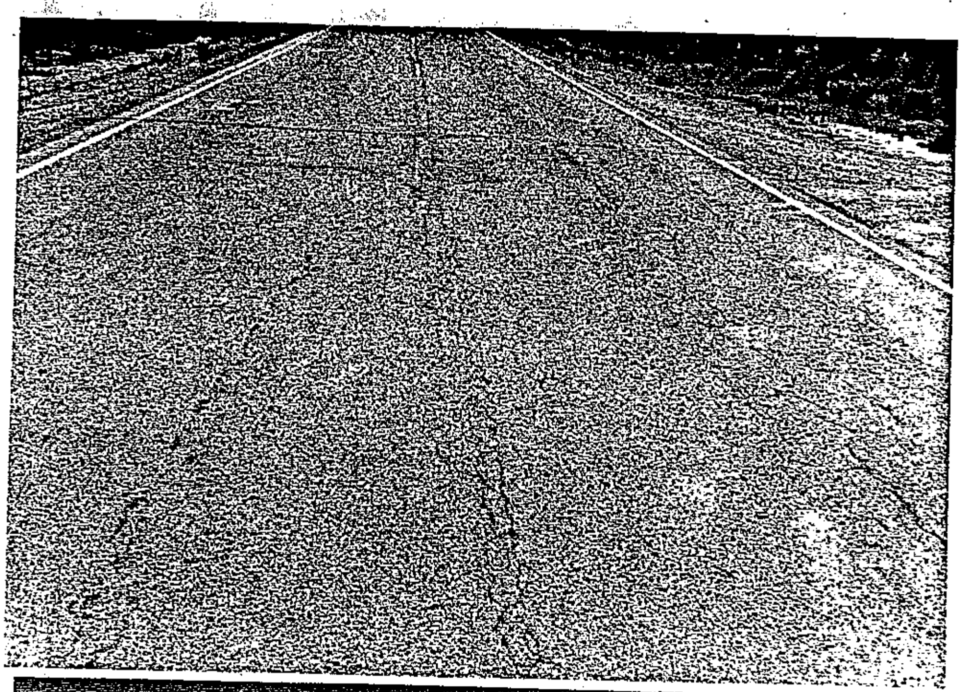
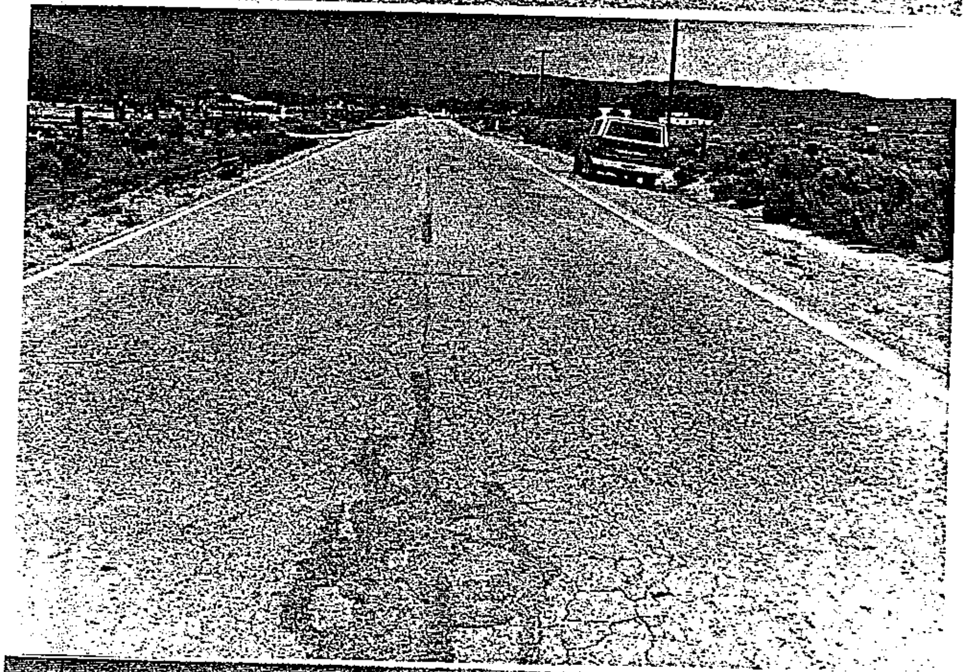


Figure 3

Benton Test Section

Pavements prior to test section installation.

SEA 40% Area



SEA 20% Area

AR-2000 Control Area

PRECONSTRUCTION LABORATORY INVESTIGATION

Prior to the test section construction, samples of the aggregate, asphalt, and sulfur to be used in the test section were sent in to the TransLab to be used in preparing a mix design for each of the binders that would be used. As indicated in the introduction, the binders chosen were SEA 20 percent, SEA 40 percent, and the untreated AR-2000 control asphalt. The source of the asphalt (Newhall) used in this test section is the same as in the Baker Test Section.

Procedures used in obtaining the designs were the same as those used for the Baker Test Section. This consisted of using dry sulfur in preparing the design mixes to insure accuracy in determining the correct amounts of sulfur and asphalt. Design details are as follows:

Design Method: Hveem (California Test 367)

Mix type, size, and grading: Type A, 1/2" maximum, coarse grading. (Caltrans Standard Specs. Section 39)

Aggregate source: Milner Fan Pit (at PM 7.8 on east side US 6)

Aggregate Properties:

Specific Gravity - (California Test 105)
Coarse 2.64 Fine 2.67

LART (California Test 211) Abrasion loss (grams) to 500 Rev. = 19%

CKE: (California Test 303)

Kc = 0.9   Kf = 1.0   Km = 1.0
Surface Area = 26.3

Sand Equivalent: (California Test 217) = 79

Asphalt: AR-2000 (Newhall)

Binders: AR-2000, SEA 20%, SEA 40%

Sulfur: Commercial Grade 99.4% pure (powdered)

Temperatures Used: Aggregate 300°F, Binder 300°F

LAB Mixing Procedure: Using carefully weighed quantities, add asphalt to aggregate, pour into mixer and add powdered sulfur to mix as it starts mixing. Continue mixing until aggregate is completely coated and odor of sulfur is strong, indicating that the sulfur has melted.

Design Binder Content Recommendations

Binder	Percent Binder*	Design Briquettes Hveem Stability	Design Briquettes Voids(%)
AR-2000	5.5	38	4.5
SEA 20 %	6.0	39	4.5
SEA 40 %	7.5	46	4.8

*By dry aggregate

Marshall Test (AASHTO T245) Results of Laboratory Mixes Using Actual Job Binder Contents Used In The Field

Binder	Binder Content (%)*	Stability (Pounds)	Flow (0.01 Inch)
AR-2000	5.4	1184	0.20
SEA 20 %	6.0	1430	0.15
SEA 40 %	7.5	1790	0.17

*By weight of dry aggregate.

TEST SECTION CONSTRUCTION

The construction of the cold weather test section took place between May 30 and June 4, 1984 (Figure 2). Work on the contract, of which the test sections are a part, had resumed approximately a month prior to the test section construction after a winter shutdown. Weather conditions during the test section construction were variable, ranging from sunny to cloudy with temperatures ranging from 68 to 80°F. No rain occurred during the construction period.

I. Mixing Operations

The hot plant, which was located at the aggregate source (Milner Fan Pit at Road 09-Mno-6-7.8), was a Stans Steel 10,000 pound batch plant. The haul distance was approximately 17 miles.

Since the SEA job was small and at a remote location, the contractor was unable to economically obtain a blender to preblend the sulfur and asphalt. Therefore, the blending was accomplished in the pug mill after the asphalt and sulfur components had been weighed in the weigh bucket. Although this method makes it impossible to sample the blended binder, it is felt that it is also one of the most positive methods of accurately measuring the proper amount of each component. The sulfur was piped to the weigh bucket in a jacketed heated line from the tank trailer. No problems were experienced in the mixing process other than some trouble with the conveyer system taking the new mix to the surge silo.

SEA operations were to begin during the morning of June 4 but conveyer problems delayed the first load of SEA until about 1 p.m. No more delays occurred during the afternoon so that all of the SEA sections were laid by approximately 4:30 p.m. Temperature control at the plant was fairly good with most of the mix reaching the street between 280 and 290°F. Figure 4 shows some hot plant details.

II. Paving Operations

The paving operation went smoothly for both the control and SEA sections with no discernible differences evident because of the SEA. Table 1 presents the paving dates and temperature details of the installation. Figure 5 shows paving sequences with the SEA. Paving equipment used during the test section installation consisted of a Barber-Green Model SB 170 rubber tired paver with a KoKal windrow loader. Compaction was accomplished by a DynaPac Vibro Plus Model CC50A (16 ton) steel roller using two coverages at 3 mph at 2400 VPM frequency (high amplitude) for the breakdown rolling. Finish rolling was done with a Gallion 8-ton steel roller performing two coverages. Figures 6, 7, and 8 show new and 16-month views of the pavement surfaces. Nuclear densities were determined 10 days after the test section construction. The results which follow indicate that all the sections, excluding shoulders, received a minimum 95% $\pm$ relative compaction compared with the laboratory design densities. The results also show that the SEA 40% section ended up with the highest relative compaction. This was also true in the Baker Test Section(1).

Section	Laboratory Design Density	Field Density (Nuclear)	%Relative Compaction $\frac{\text{Field Den.}}{\text{Design Den.}}$ X100	Theoretical Max. Sp. Gr.	% Field Voids $\frac{\text{Field Density}}{\text{Theo. Max Sig.}}$ X100 -100
AR-2000 Control	2.31	2.21	95.7	2.45	9.8
NB Shoulder AR-2000	2.31	2.15	93.1	2.45	12.2
SEA 20%	2.33	2.22	95.3	2.46	9.8
SEA 40%	2.31	2.25	97.4	2.44	7.8
NB Shoulder SEA 40% Section	2.31	2.09	90.5	2.44	14.2

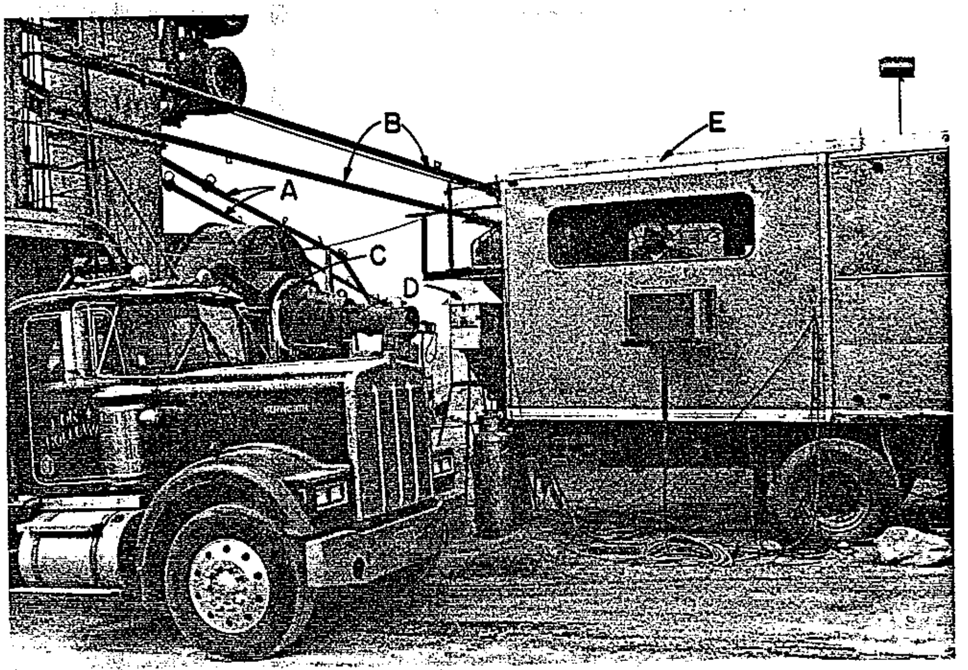
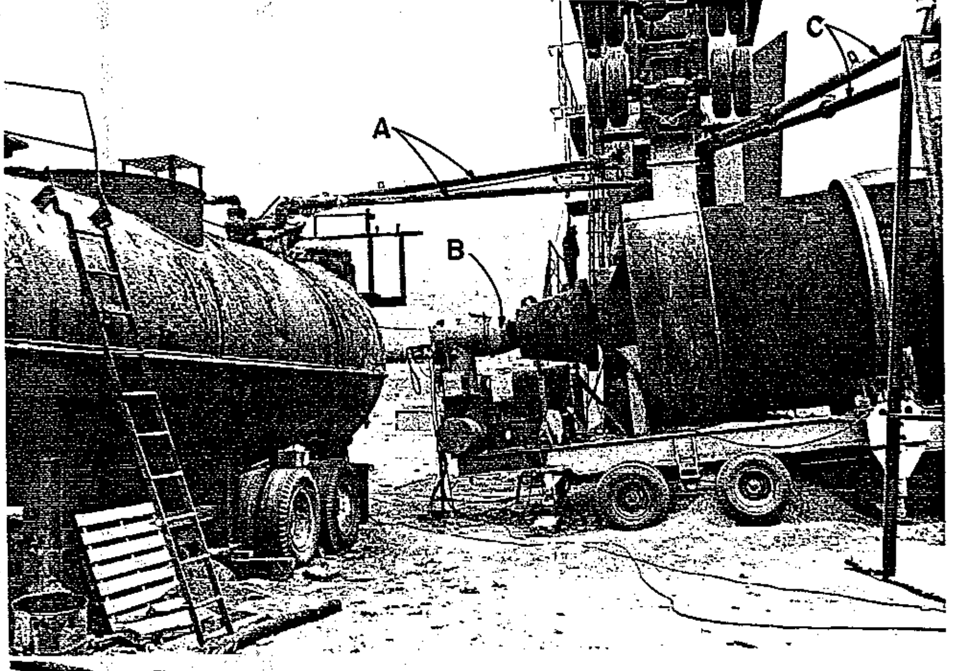


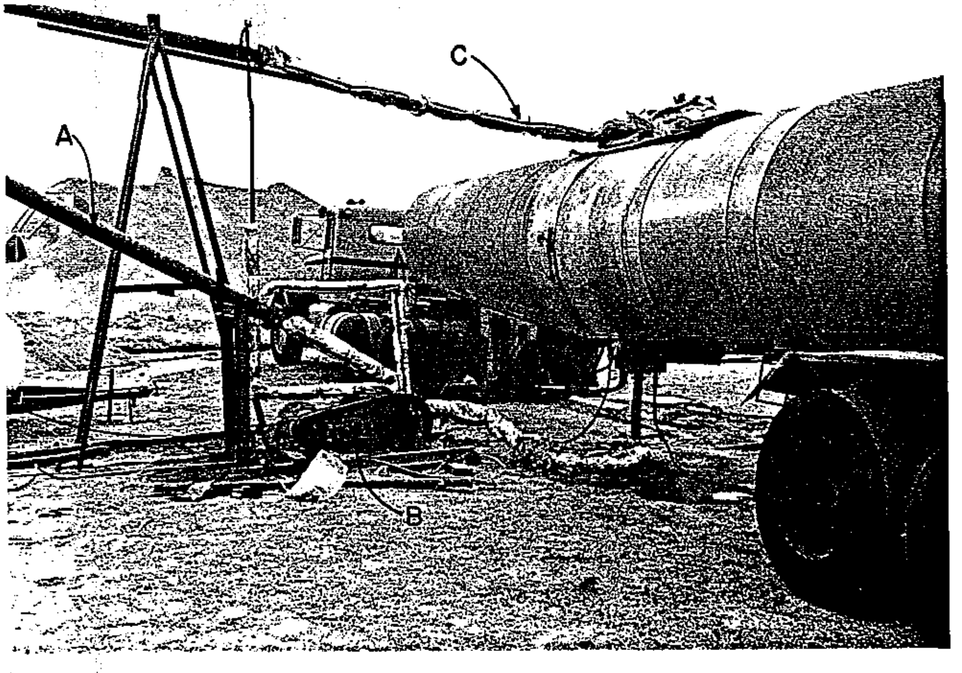
Figure 4

Mixing plant views showing sulfur piping.

View showing sulfur piping (A), regular asphalt piping (B), burner (C), high-volume air sampler ("D" for particulates), and control room (E).



Reverse view showing asphalt tank & piping (A), aggregate dryer-burner (B), sulfur piping (C).



View showing piping, pump, & sulfur tank. Feed line (A), pump ("B" from bottom) and sulfur return line at top (C).

TABLE 1

BENTON TEST SECTION INSTALLATION

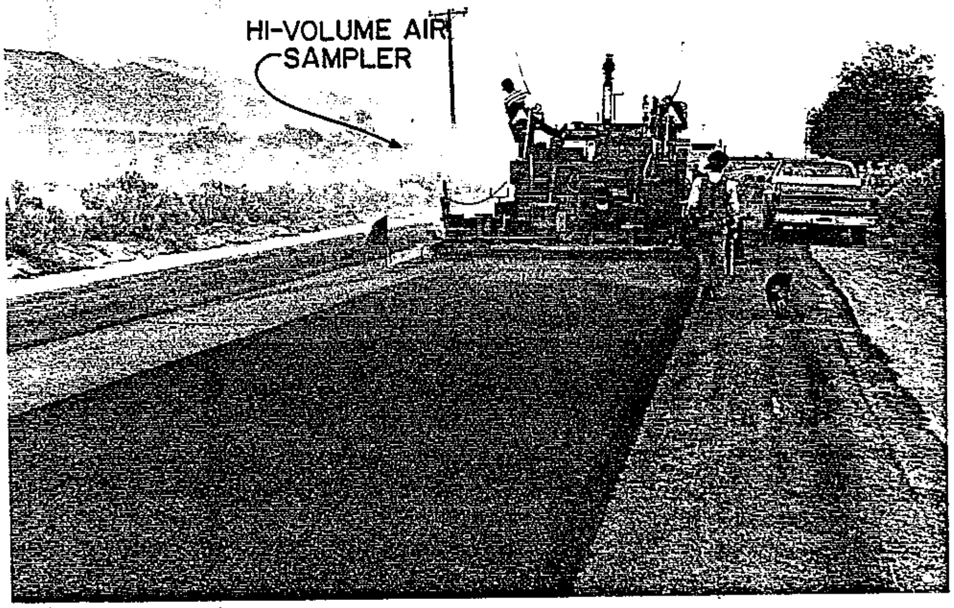
Paving Dates, Conditions, and Details

Date	Section	Location Station	Location Lane	Design Thickness (Feet)	Mix Temperatures (°F Avg.) Plant	Windrow	Laydown	Breakdown	Finish	Weather Cond.	Temp °F
5-30-84 (PM)	AR-2000	1334-1347	NB SB	0.15	300	285	260	230	170	Cloudy	80
5-31-84 (AM)	AR-2000	1325-1334	NB SB	0.15	-	260	250	230	-	Clear	72/80
6-4-84 (PM)	SEA 20%	1310-1325 1312+50-1325	NB SB	0.15	286	276	260	230	-	Cloudy	71
6-4-84 (PM)	SEA 40%	1299-1310 1299-1312+50	NB SB	0.15	286	282	273	253	-	Cloudy	71
6-4-84 (Late PM)	SEA 40%	1324+20-1327+60 NB Shoulder		0.15	(No Temperatures)					Cloudy	68

Figure 5

SEA Paving Views
(6-4-84)

Mix placed in windrow. Using gas detection analyzer to determine H_2S or SO_2. Note inspector wearing dust mask.



Smoke from pavement immediately following paver.

Note Hi-Volume air sampler to left of paver across road near power pole.

Breakdown rolling with vibratory compactor.

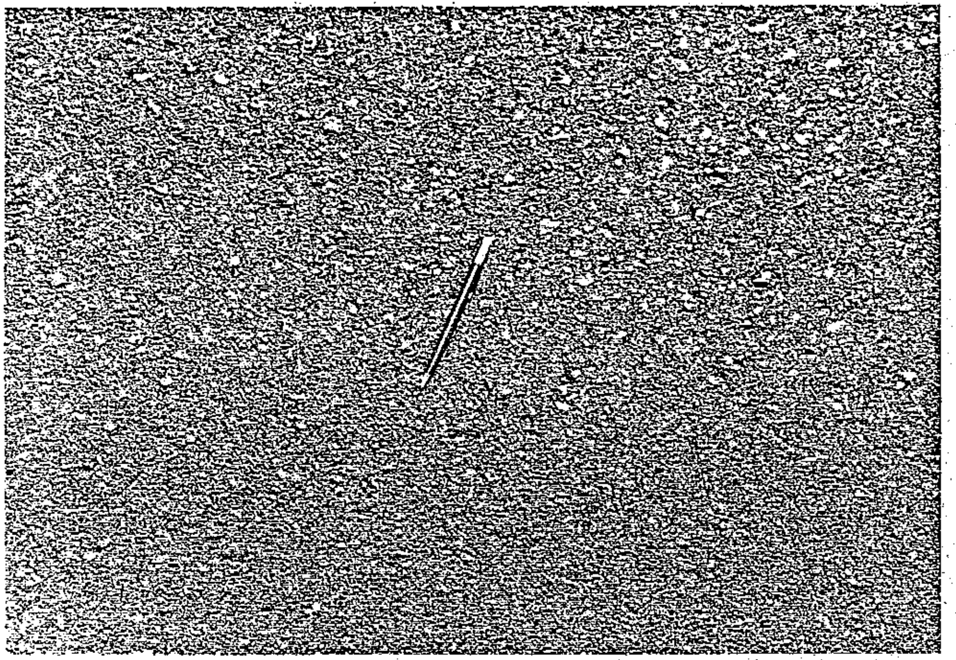
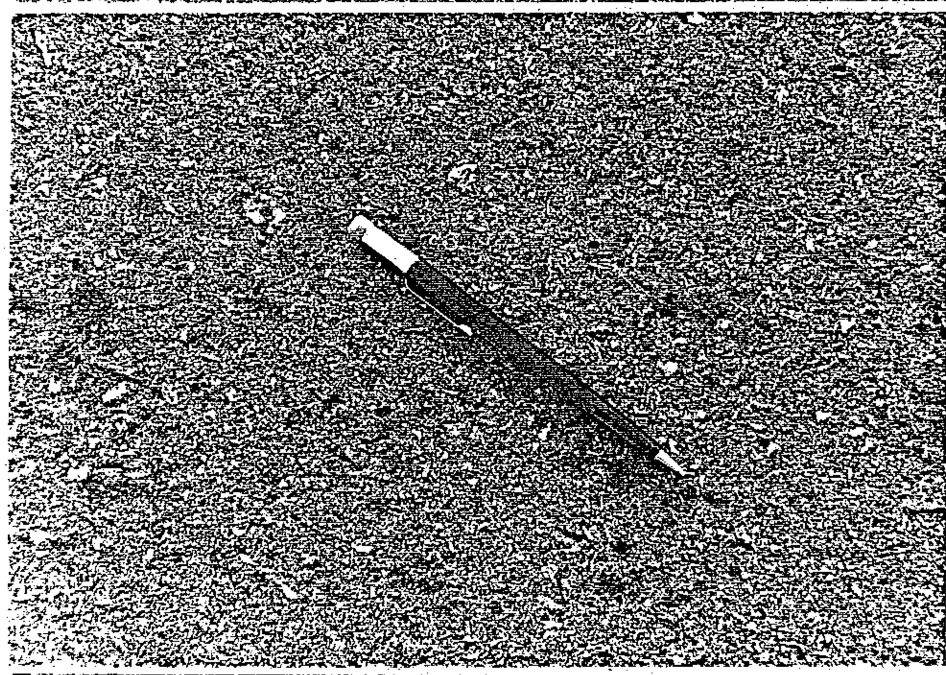


Figure 6

Surface views of AR-2000 (control) pavement.

New Pavement

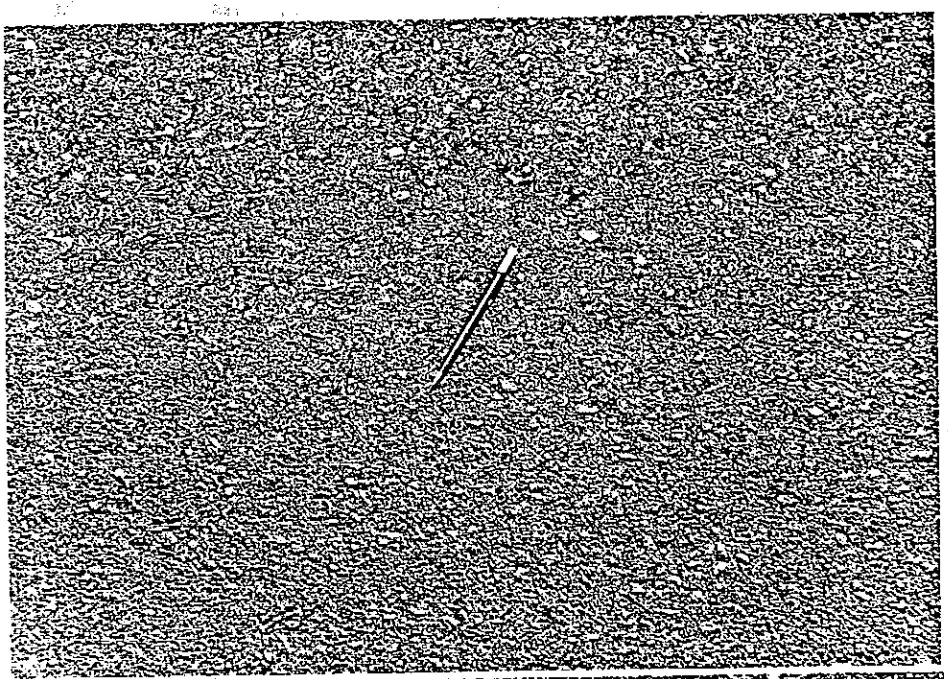


NB Lane after 16 months.

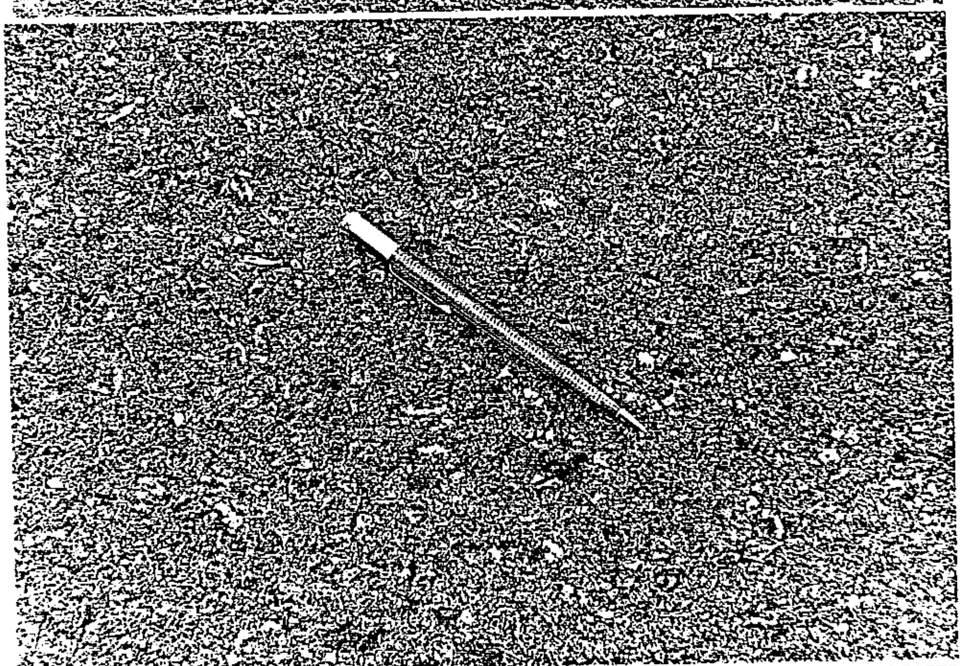
SB Lane after 16 months.

Figure 7

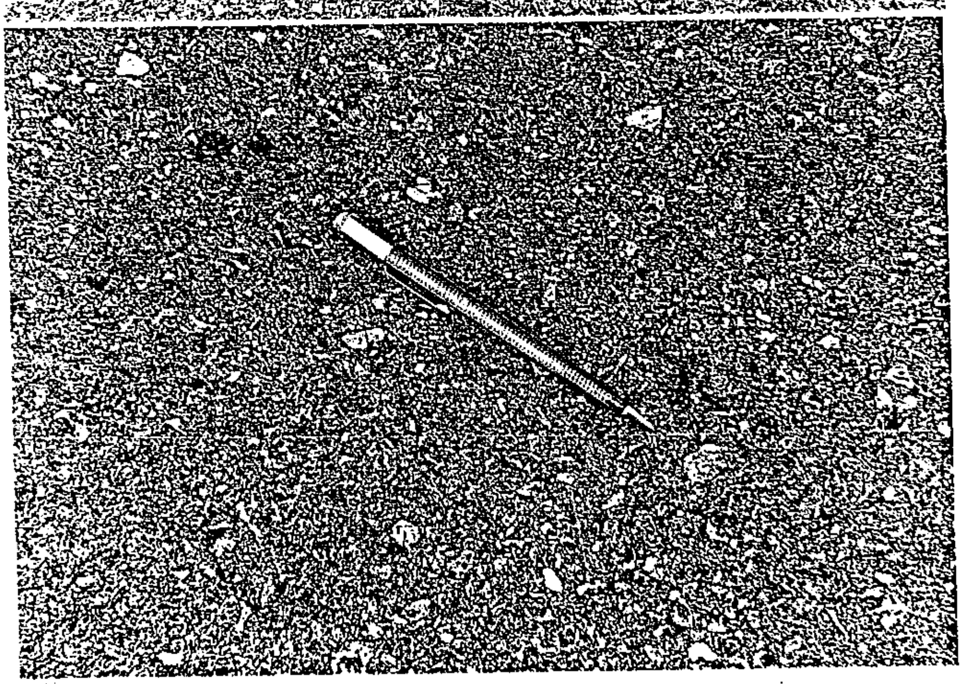
Surface views of SEA 20% pavement.



New Pavement



NB Lane after 16 months. (wheel track)



SB Lane after 16 months. (wheel track)

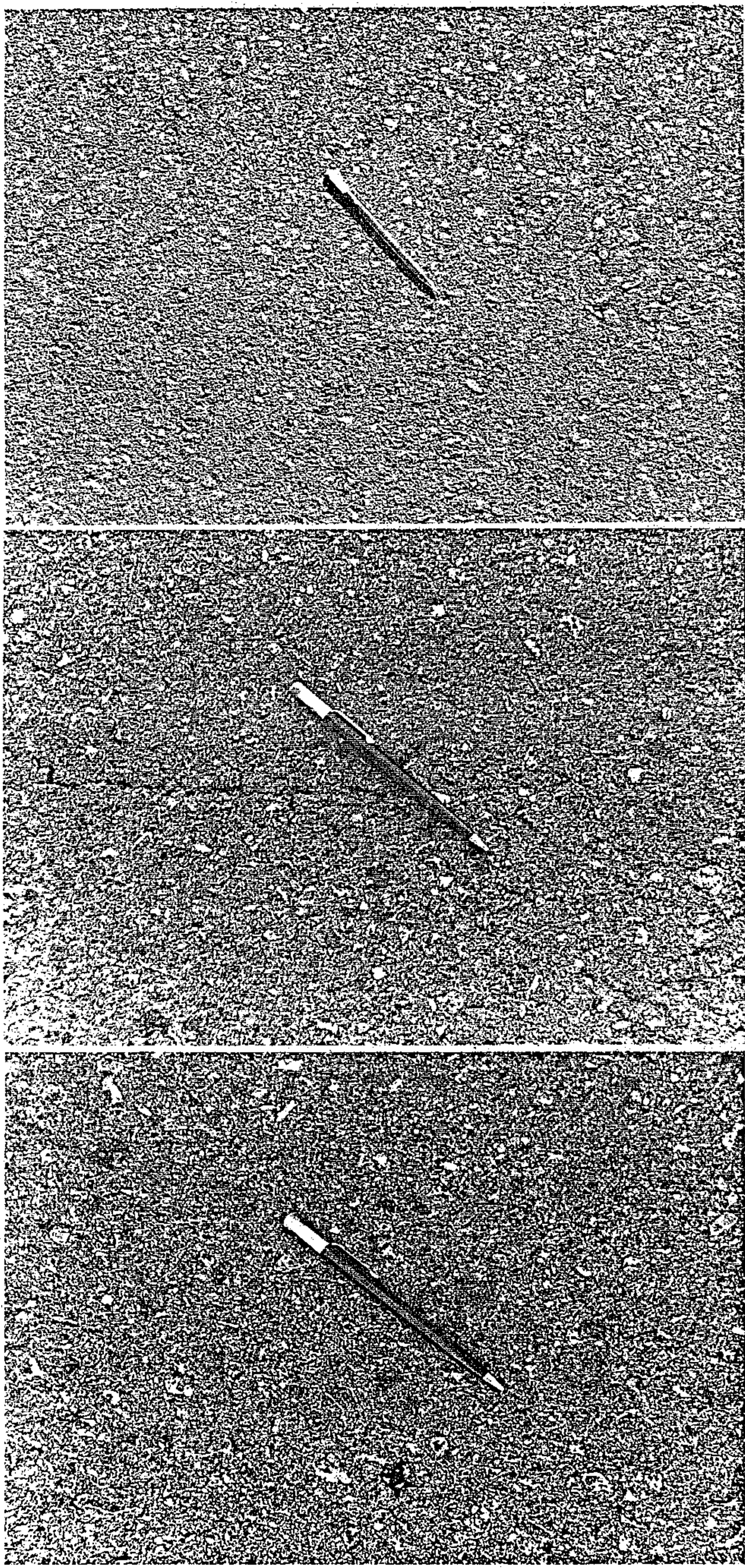


Figure 8

Surface views of SEA 40% pavement.

New Pavement

NB Lane after 16 months. (Wheel track at location of reflection crack.)

SB Lane after 16 months. (wheel track)

III. Environmental Measurements

Since the contract under which this test section was placed required that safe levels of H_2S sand SO_2 be maintained in the work areas on the street and at the hot plant, efforts were made to determine the existence and quantity of H_2S and SO_2 gases generated in the SEA mixes with several gas detection devices. Table 2 presents the possible effects of H_2S and SO_2. In addition, other devices were used to determine the presence and quantity of suspended particulates (dust) and whether sulfates and free sulfur were a part of those particulates, this also in the areas of work on the street and around the hot plant. The devices included:

A. Short-Term Exposure Devices:

a. H_2S = Interscan Model 1176 portable gas detection analyzer, ranges: 0-10/0-100 ppm.

b. SO_2 = Interscan Model 1248 portable gas detection analyzer with H_2S scrubber, ranges: 0-10/0-25/0-50 ppm.

B. Long-Term Exposure Devices:

Drager Polymeter with long duration tubes for determining concentration of H_2S and SO_2. It was necessary to determine each gas concentration separately at different times.

TABLE 2

TOXICITY OF HYDROGEN SULFIDE AND SULFUR DIOXIDE

Hydrogen Sulfide (H_2S)*

Concentration (ppm)	Effect
>0.03	Odor detectable (rotten eggs).
3	Odor offensive, failure of sense of smell within a few minutes.
10	Threshold Level Value (TLV)-Time Weighted Average (TWA) (ACGIH).
15	TLV-STEW (Short-Term Exposure Limit) (ACGIH)
>20	Irritancy of eyes and respiratory tract which increases with concentration and exposure time.
200	Immediate failure of sense of smell.
300-500	Less than 1/2 hour exposure can result in headache, dizziness, staggering gait, nausea, and dryness and pain in the respiratory tract, (followed later by bronchitis and pulmonary edema).
>600	A few minutes exposure can be dangerous with increasing systemic and CNS involvement in addition to irritancy and edema.
1000-2000	Paralysis of the breathing centers can occur after a few breaths followed by collapse and quick death if removal to fresh air and restoral of breathing is not rapidly accomplished.

Sulfur Dioxide (SO_2)*

Concentration(ppm)	Effect
0.47	Detected by taste.
3-5	Noticable odor.
2	TLV-TWA (ACGIH)
5	TLV-STEL (ACGIH)
>6	Immediate irritation to nose and throat (sneezing and coughing).
20	Irritation to eyes, smarting and tearing.
50-100	Maximum Allowable Concentration for 30-60 minutes exposure, can be dangerous
400-500	Immediately dangerous to life.

*Data from:

1. Hydrogen Sulfide, Material Safety Data Sheet No. 52
   General Electric Co., Schenectady, NY (12-1979)

2. Sulfur Dioxide, Material Safety Data Sheet No. 50
   General Electric Co., Schenectady, NY (12-1979)

C. Suspended Particulates (Dust), Sulfates, and Free Sulfur:

Two General Metals Hi-Volume Air Samplers, each with a Sierra Instruments Flow Controller which regulated the air flow to 40 CFM, were used. One unit was used at the hot plant and the other unit was set up alongside the road in the vicinity of the paving operation. The air is drawn through a paper filter which is weighed to determine the total suspended particulates (TSP), then portions (1/4) of the filter are analyzed for sulfates and free sulfur. The procedures used are:

1. Sulfates: AIHL (Air Industrial Hygiene Laboratory of the U.S. Dept. of Public Health) Method No. 61 (Turbidimetric Barium Sulfate)

2. Free Sulfur: AOAC (Association of Official Analytical Chemist) Method for free sulfur in fertilizer (Modified) 11th Edition 1970, page 31, paragraph 2.140.

D. Regulations

1. H_2S and SO_2

Authority: Cal-OSHA Title 8, California Administrative Code, General Industry Safety Order, Section 5155 (Airborne Contaminants)

a. Hydrogen Sulfide (H_2S) = Register 84, No. 39-9-29-84.

Table AC-2 Excursion Exposures

Permissible Exposure Limit (PEL) ppm	mg/m³ (25C 760 mmHg)	Excursion Limit (ppm)	Excursion Duration	Ceiling Limit (ppm)
10	15	20	10min/8hr	50

b. Sulfur Dioxide (SO_2) = Register 84, No. 10-3-10-84

Table AC-1, Chemical Contaminants:

Permissible Exposure Limit (PEL) = 3.5 ppm, 9 mg/m^3 (25c, 760 mm Hg)

2. Suspended Particulates (TSP), Sulfates, Free Sulfur

Particulate levels and associated sulfate and free sulfur amounts were compared to worker environment limits set forth by Cal-OSHA, Title 8, Administrative Code, General Industry Safety order, Section 5155, Register 84, No. 39-9-29-84 as follows:

Nuisance Dust = TLV (30 mppcf) or 10 mg/m^3 of total dust and 5 mg/m^3 (respirable dust), and Materials Safety Data Sheet No. 56: Sulfur = 10mg/m^3 (total dust) or 5 mg/m^3 (respirable dust)

E. Operations and Results

Monitoring of the street and hot plant work areas took place throughout the installation of the test sections.

Readings obtained with the various detection devices are shown on Table 3.

F. Analysis of Test Results

The results presented in Table 3 indicate that the areas where workers would normally be present were within Cal-OSHA requirements for the levels of H_2S and SO_2. Momentary bursts near the storage hopper at the plant were above the requirements as was a reading taken when the sampling probe measured the fumes in the auger area of the paver, but these are not areas where workers would normally work. Nuisance dust particulate levels were very much influenced by wind direction and velocity. The nuisance dust readings at the plant showed an above specification reading on the day the control section was being paved, but on the day of SEA production the reading was quite low. The highest free sulfur readings were along the street during the SEA paving operation with virtually no free sulfur evident at any of the other sites.

TABLE 3

ENVIRONMENTAL SAMPLING RESULTS

Paving Material	Date	Weather Conditions	Temp. °F	Sampling* Location (of Hi-Vol Sampler)	Short Duration* (Interscan)			Long Duration* (Dreager)		Particulates** (Hi-Vol Air Sampler)		
						H_2S (ppm)	SO_2 (ppm)	H_2S (ppm)	SO_2 (ppm)	TSP mg/m^3	Sulfates mg/m^3	Free Sulfur mg/m^3
AR-2000 (Control)	5-31 pm	Sunny South winds 10-15 mph (wind blew toward H-Vol Samp. at plant)	72-80	Plant						22.5	0.048	0.00007
				Street (at Sta 1330 approx, west road-side)						0.19	0.013	0.0
SEA 20%	6-4 pm	Cloudy North winds 10-20 mph (wind blew away from Hi-Vol Samp. at plant)	72-68	Plant	Windrow	2	0	On 0.87 paver	0	1.62	0.0	0.0
					Auger	2	0					
					Roadside	0	0					
			71-68	Street (at Sta 1306-east road-side)						0.49	0.022	0.076
SEA 40%	6-4 pm	Same as SEA 20%	Same as SEA 20%		Windrow	4	4					
					Auger	-	20					
					On paver	1	-					
					Roadside	-	2					
					At Hi-vol samp.	0	1					
					Momentarily at plant down wind of hopper.	8	12					

*Sampling locations listed are for Hi-Vol sampler. Sampling locations with portable analyzer for H_2S and SO_2 were within the sections during paving operations. Specific locations are listed next to short duration and long duration results.

**Hi-Vol = General Metal High Volume Air Sampler (same location at plant for all materials.)
T.S.P. = Total Suspended Particulates
Sulfates = determined by AIHL Method No. 61 (Turbidimetric Barium Sulfate)
Free Sulfur = determined by AOAC Method for free sulfur in fertilizer (modified), 11th Edition, 1970, page 3, para. 2,140.

POSTCONSTRUCTION TESTING

During the construction of the test sections, samples of the mix were taken from the windrows and samples of the AR-2000 binder and liquid sulfur were taken at the mixing plant. As mentioned previously, it was not possible to take samples of the SEA binders. The various samples of materials were brought to the TransLab in Sacramento for testing and analysis. Additionally, as mentioned earlier, nuclear densities were determined 10 days after the installation was completed. Other field tests were performed as equipment was available.

I. Laboratory Testing of Construction Samples

A. AC Mix Samples From Windrow

Testing of the windrow mix samples was started as soon as possible after their arrival at the TransLab. Results of the testing are presented on Tables 4, 5, 6, and 7. Grading results shown on Table 4 indicate that the gradings of the SEA mixes were somewhat coarser than the grading of the control mixes. In both cases, the gradings met the specifications. The results indicate that the actual binder contents shown on Table 4 closely complied with the design binder contents. Results of tests performed on briquettes fabricated from the windrow mix samples and reported on Table 5 indicate that the mix used in the construction of the test sections compared favorably with the design mixes regarding stability, etc. In addition, the results on Table 5 indicate a slight reduction in Hveem Stability of the AR-2000 control briquettes which had undergone the moisture vapor susceptibility (MVS) (California Test 307) regime

TABLE 4

AC MIX EXTRACTION TEST DATA* (California Test 310)

Sieve Size	Operating Range (1/2" Coarse)	Grading (Percent Passing) AR-2000 (Control Section) (5-30)	(5-31)	Avg	SEA 20% Section (6-4)	SEA 40% Section (6-4)
3/4"	100	100	100	100	100	100
1/2"	95-100	96	99	97	97	97
3/8"	75-90	83	86	84	84	84
No. 4	50-66	62	66	63	55	55
No. 8	35-50	41	46	43	41	40
No. 16		29	33	30	30	29
No. 30	15-30	20	23	21	21	21
No. 50		13	16	14	14	13
No. 100		8	10	9	9	7
No. 200	3-7	5.2	7.0	5.8	5.7	4.7
Design/Binder Content (California Test 367)	%		5.5		6.0	7.5
Constructed Binder Content (California Test 310)	%	5.2	5.3	5.2	5.7	7.4

*All mix samples from windrow were tested at TransLab-Sacramento; test results are averages of two samples except for AR-2000 (5-31) value.

TABLE 5

CONSTRUCTION AC MIX SAMPLE DATA (WINDROW SAMPLES)*

Test Section	Sample Number	Stability (Calif. T366) Regular	Stability (Calif. T366) MVS**	Cohesion (Calif. T306) Regular	Cohesion (Calif. T306) MVS**	MVS** (Calif. T307) (% Moisture Absorbed)	M_R (ASTM-D4123-82) (psi x 10_5)	Surface Abrasion (Calif. T360) (Grams Loss) Rubber	Surface Abrasion (Calif. T360) (Grams Loss) Steel	Waxed Specific Gravity (Calif. T308)	Rice Sp. Gr. AASHTO T-209
AR-2000 (Control)	842-91	41	28	202	275	0.30	3.25	0.60	38.2	2.33	2.46
	842-92	37	33	161	184	0.10	2.90	0.30	33.3	2.30	2.47
	842-93	41	31	146	317	0.20	3.35	0.30	30.4	2.32	2.47
	Average	40	31	170	259	0.20	3.17	0.40	34.0	2.32	2.47
SEA 20%	842-94	39	36	175	304	0.20	3.60	0.50	36.2	2.34	2.49
	842-96	42	38	247	-	0.20	3.31	0.50	35.5	2.34	2.47
	Average	41	37	211	304	0.20	3.46	0.50	35.8	2.34	2.48
SEA 40%	842-95	43	41	227	-	0.25	4.09	0.60	35.4	2.31	2.45
	842-97	41	38	229	-	0.20	3.20	0.50	39.8	2.31	2.46
	Average	42	40	228	-	0.23	3.64	0.55	37.6	2.31	2.46

* Tested at TRANSLAB - SACRAMENTO

** Specimens which have been subjected to the Moisture Vapor Susceptibility Procedure (MVS)

TABLE 6

RECOVERED BINDER DATA (FROM WINDROW AC MIX SAMPLES)

Test Section	Sample Number	TEST ON ABSON RESIDUE (Calif. 380): Absolute Vis. at 140°F AASHTO-T202 (poise)	Kinematic Vis. at 275°F T201 (cSt)	Penetration T49 at 77°F (dmm)	Penetration T49 at 39.2°F (dmm)	Softening Point T-53 (°F)	Ductility T51 at 71°F (cm)	Ductility T51 at 39.2°F (cm)	TEST ON MICRO RECOVERIES (Calif. 365): Micro Viscosity at 77°F Cal. T348 at $0.05S^{-1}$ (megapoise)	Micro Viscosity at 77°F Cal. T348 at $0.001S^{-1}$ (megapoise)	Shear Susceptibility Cal. T348 slope	Micro-Ductility at 77°F Cal. T349 (mm)
AR2000 (Control)	842-91	1654	267	50	17	122	150+	5.5	2.8	2.9	0.01	105
	842-92	2482	304	43	14	125	150+	0.5	4.9	4.9	0.0	58
	842-93	1939	308	52	15	123	150+	1.5	3.2	3.8	0.05	49
	Average	2025	293	50	15	123	150+	2.5	3.6	3.9	0.02	71
SEA 20%	842-94	1680	164	53	16	123	79	1.2	5.6	6.2	0.03	35
	842-96	1274	144	59	16	121	109	2.0	4.9	6.4	0.07	28
	Average	1477	154	56	16	122	94	1.6	5.2	6.3	0.05	31
SEA 40%	842-95	1875	167	52	15	123	102	1.7	10.7	17.0	0.12	15
	842-97	1336	133	63	18	119	66	1.5	3.6	7.5	0.18	27
	Average	1605	150	57	17	121	84	1.6	7.1	12.2	0.15	21

TABLE 7

ASH AND SULFUR CONTENT DATA*

Test Section	ORIGINAL BINDERS** Sample Number	Percent Ash	Percent Sulfur	ABSON RECOVERED BINDERS*** Sample Number	Percent Ash	Percent Sulfur
AR-2000 (Control)	R5120	-	2.0	842-91	0.76	1.92
	R5122	-	2.1	842-92	1.35	2.12
				842-93	0.44	2.02
SEA 20% (Laboratory Mixed)	R5120+ Sulfur		18.9	842-94	0.63	19.1
				842-96	0.85	19.6
SEA 40% (Laboratory Mixed)	R5120+ Sulfur		29.2	842-95	0.49	19.6
				842-97	0.69	20.3

ON RESIDUE from CATOD (California Test 374)****

Test Section	Sample Number	Percent Ash	Percent Sulfur
AR 2000	R5120	-	2.14
	R5122	-	2.0
SEA 20%	R5120+ Sulfur	-	15.2
SEA 40%	R5120+ Sulfur	-	36.9

*Ash determination - ASTM D482-80 (ash from petroleum products)
Sulfur determination - LECO Induction Furnace method for petroleum products.

**Determined on binders sampled from feed line at hot plant.

***Determined on residues from Abson recovery (California Test 380) of windrow samples.

****California Tilt Over Durability (CATOD) performed on laboratory Mixed samples.

while the MVS procedure had less effect on the SEA briquettes. This reduction varies from the reduction to the MVS procedure by the control mix from the Baker Test Section(1) where the MVS did not affect the stability result significantly. It would appear from these results that the SEA binders may offer greater resistance to moisture than a conventional asphalt binder. Presented on Table 6 are the results of tests performed on the binders recovered from the windrow mixes. The results show a similar pattern to the results from the Baker Test Section(1) in that the recovered SEA binders are softer than the control binder.

Table 7 presents the results of ash and sulfur determinations run on recovered binder from the windrow mixes as well as sulfur determinations on original binders and laboratory mixed SEA binders. The results verify the experiments of Kennepohl et. al.(2) which indicated that approximately 20 percent of sulfur went into solution in a sulfur-asphalt mixture. As can be seen on Table 7, the recovered binders from the SEA 20 and 40 percent sections show this approximately 20 percent sulfur in solution.

B. Original Binder and Blended Binder Samples

Table 8 presents results of tests on samples of original binder taken at the hot plant during the construction of the test sections. As mentioned earlier, it was impossible to obtain samples of the SEA binders since the asphalt and sulfur were combined in the batch weigh bucket prior to mixing. So that the properties of the SEA binder could be obtained, SEA 20 and 40 percent blends (using the control AR-2000 and sulfur) were made in the

TABLE 8

BINDER TEST DATA

Test On Original Binder	AASHTO Designation	AR-2000 (Control)* R5120 (6-4-84)	AR-2000 (Control)* R5122 (5-31-84)	SEA BLENDS** SEA 20 %	SEA BLENDS** SEA 40 %
Penetration at 77F(25C) (dmm)	T49	76	76	108	109
at 39.2F(4C) (dmm)	T49	16	17	25	24
Penetration Ratio $\frac{39.2F\ Pen.}{77F\ Pen.}$ x 100	T49	21.1	22.4	23.1	22.0
Flash Point C.O.C. (°F)	T48	530	520		
Softening Point (°F)	T53	115	115	113	114
Solubility in Trichloroethylene (%)	T44	99.92	99.92		
Spot Test(heptane-xylene equivalent)	T102	-35	-35		
Specific Gravity at 77F(25C)	T228	1.0130	1.0173	1.1132	1.2189
at 60F(15.6C)	T228	1.0187	1.0230	1.1196	1.2258
Absolute Viscosity at 140F(60C) (poise)	T202	943	917	499	553
Kinematic Viscosity at 275F(135C) (cSt)	T201	219	216	92	98
Thin Film Loss (325F-5hr.) (%loss)	T179	0.12	0.08		
Rolling Thin Film Test (325F-85min.)(% loss)	T240	0.03	0.06		
Test on RTFC Residue (AASHTO T240)					
Absolute Viscosity at 140F(60C) (poise)	T202	2196	2147	1140	1685
Kinematic Viscosity at 275F(135C) (cSt)	T201	311	317	155	161
Penetration at 77F(25C) (dmm)	T49	47	48	64	53
at 39.2F(4C) (dmm)	T49	15	15	18	16
Percent of Original Penetration(%)	T49	61.8	63.2	59.2	48.6
Ductility at 77F(25C)-5cm/min. (cm)	T51	100+	100+	139	31
at 39.2F(4C)-1cm/min.(cm)	T51	7.0	7.2	0.9	0.5
Test on Residue from Tilt-Oven Dur. Test	*** 374				
Absolute Viscosity at 140F(60C) (poise)	T202	101468	99381	546,225	122,346
Kinematic Viscosity at 275F(135C) (cSt)	T201	1375	1365	1875	657
Penetration at 77F(25C) (dmm)	T49	12	11	11	14
Softening Point (°F)	T53	152	154	163	155
Ductility at 77F(25C)-5cm/min. (cm)	T51	5.5	5.5	1.0	1.5
Micro-Viscosity at 77F(25C)@ 0.05sec^{-1}S.R. (megapoise)	*** 348	106.0	97.0	88.0	69.5
@ 0.001sec^{-1}S.R.	*** 348	385.0	288.0	530.0	500.0
Shear Susceptibility (slope)	*** 348	.33	.28	.46	.50
Micro-Ductility at 77F(25C)-5mm/min. (mm)	*** 349	1	1	0	0

*Sampled from feed line at hot plant.

**Blended at Caltrans Lab - Sacramento of R5120 (AR2000) + Sulfur.

***California Test No.

TransLab in Sacramento and then tested. These test results are also presented in Table 8.

C. Durability Testing and Predictions of the Binders

In addition to conventional asphalt test procedures, the California Tilt-Oven Durability (CATOD - California Test 374) test was performed on the original and blended binders. Test results are presented in Table 8. The results followed the same pattern as the test results obtained on the Baker Test Section binders(1). Further testing of field aged samples will help to determine whether these results are reliable predictors of the SEA blend's durability.

II. Field Testing and Evaluation

Due to the remoteness of the test site, difficulties were encountered when trying to complete the initial testing. Thus, some of this initial testing was not accomplished until several months after the test sections were constructed. Skid resistance (Table 9) and deflection data (Table 10) are reported as indicated on the respective tables. Tolerable deflection values shown on Table 10, which are based on the thickness of the overlay in each lane as the flexible layer and the amount of truck traffic, indicate that both lanes were on the tolerable deflection borderline at the time of the deflection measurements (1985). Generally the results indicate a fairly well constructed test section. A crack and condition survey was made prior to the installation of the test sections and a similar survey was conducted 16 months after construction. Table 11 presents the results of both surveys. The preinstallation results show that the roadway was severely cracked throughout most of the test areas with many transverse cracks and

TABLE 9

SKID TEST RESULTS (ASTM E-274) SN40 (8 Months)

Section	Location	SKID NUMBERS NB Lane Run 1	NB Lane Run 2	NB Lane Avg.	SB Lane Run 1	SB Lane Run 2	SB Lane Avg.
SEA 40%	NB PM 24.58 to 24.79 SB PM 24.82 to 24.58	52	52	52	51	52	52
SEA 20%	NB PM 24.79 to 25.07 SB PM 25.07 to 24.82	54	56	55	52	55	53
AR-2000 (Control)	NB PM 25.07 to 25.48 SB PM 25.48 to 25.07	52	53	52	52	52	52

TABLE 10

DEFLECTION DATA*

			Deflections (Inches)				Tolerable** Deflection (inches)	
			NB Lane		SB Lane			
Section	Test Section Location	Deflection Location	Mean Deflection	80th Percentile	Mean Deflection	80th Percentile	NB	SB
SEA 40%	PM 24.58 to 24.79	PM 24.6 to 24.8	0.015	0.018			0.023	
	PM 24.82 to 24.58	PM 24.84 to 24.603			0.018	0.021		0.020
SEA 20%	PM 24.79 to 25.07	PM 24.81 to 25.08	0.021	0.025			0.023	
	PM 25.07 to 24.82	PM 25.085 to 24.846			0.020	0.022		0.020
Control (AR-2000)	PM 25.07 to 25.48	PM 25.09 to 25.45	0.021	0.024			0.023	
	PM 25.48 to 25.07	PM 25.45 to 25.09			0.017	0.020		0.020

*Readings obtained June 4, 1985 (12 months after construction) using California Test 356 (Dynaflect). Values are equivalent Deflectometer readings.

**Tolerable Deflection for each lane determined by California Test 356 based on the thickness of the overlay in the northbound lane (Table 11) of 0.16 feet average thickness and 0.25 feet average thickness in the southbound lane.

Note: Deflection data determined in 1980 indicated mean deflections of 0.014 inches in both the northbound and southbound lanes. The 80th percentile values were 0.019 inches in the northbound lane and 0.018 inches in the southbound.

TABLE 11

Condition and Crack Survey

Test Section Installed June 1984

Section	SB LANE Length (ft)	SB LANE Orig (8-83)	SB LANE 16 mo. (10-85)	NB LANE Length (ft)	NB LANE Orig (8-83)	NB LANE 16 mo. (10-85)
AR-2000	2200'	2200'	0	2200'	1830'	68'
(Control)	% Total Cracked	100%	0	%	83.2%	3.1%
	No. Transverse Cracks	164	0	No.	123	4
	% Reflection Cracks		0	%		3.3%
SEA 20%	1250	1250'	0	1500'	1480'	1
	% Total Cracked	100%	0	%	98.7%	0.1%
	No. Transverse Cracks	90	0	No.	82	1*
	% Reflection Cracks		0	%		1.2%
SEA 40%	1350	1315'	9'	1100'	798'	20'
	% Total Cracked	97.4%	0.7%	%	72.5%	1.8%
	No. Transverse Cracks	74	9*	No.	47	20*
	% Reflection Cracks		12.1%	%		42.5%
SEA 40%				340'	(New	0
NB Shoulder				% Total Cracked	Shoulder)	0
Sta 1324+20 to 1327+60				No. Transverse Cracks	(No Data)	0
Control				340'	(New	0
Shoulder				% Total Cracked	Shoulder)	0
NB Adjoining				No. Transverse Cracks	(No Data)	0
Sta 1327+60 to 1331						

*reflection cracks

block cracking. The 16-month survey shows significant (42.5%) reflection of transverse cracks in the northbound lane of the SEA 40 percent section (12.1% reflection cracking in southbound lane)(Figure 9); also, one reflection crack near the transition of the SEA 40% to SEA 20% in the SEA 20 section. No reflection cracking is evident in the AR-2000 control section. No other cracking is evident in the SEA sections, but some longitudinal and block cracking is showing in an area of the AR-2000 control. It is felt that the greater prevalence of reflection cracking in the SEA 40% section compared to the SEA 20% section is possibly due to increased rigidity of the SEA 40% section because of the larger amount of free sulfur in the SEA 40% binder. This road receives a significant amount of heavy truck traffic during the winter months.

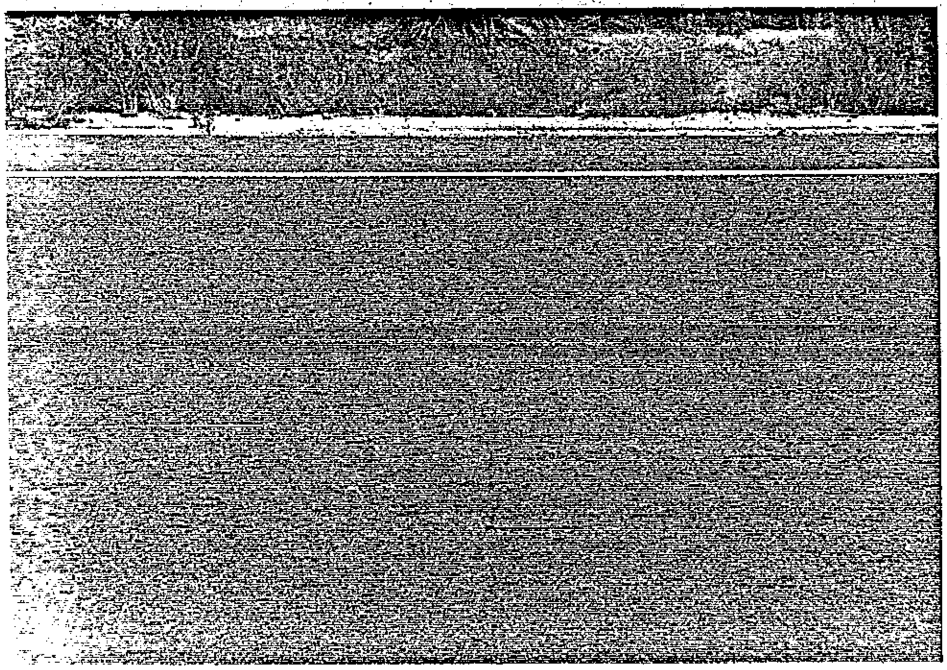
III. Core Removal and Testing (11 Months)

The first coring of the Benton Test Section occurred 11 months after the installation of the test sections. Two sets of cores were removed from each test area in each lanes. Each set consisted of six 4-inch cores and two 12-inch cores.

Prior to sawing or testing, the cores were examined and measured to accurately determine the test layer thickness. The thicknesses are shown in Table 12. The thickness data indicate that both lanes meet the design thickness, but also that the southbound lane is approximately 0.10 foot thicker. Whether this was planned or a paver malfunction is unknown, but it affords an opportunity to study a thicker section. This variation in thickness between the northbound and southbound lanes could explain the difference in reflection cracking cited previously.

Figure 9

Views of a reflection crack in SEA 40% pavement area.



Across

Close-Up
Note spalling on edge of crack.

TABLE 12

DENSITY AND THICKNESS DATA
(11 Months After Construction)*

Test Section	Lane No.	Theoretical Max. Sp. Gr. (Cal. T367)	LAB** Sp. Gr. (Cal. T308)	Waxed Sp. Gr. (Cal. T308)	Relative Density (%) (Cal. T367)	% Voids (Cal. T367)	Relative Compaction (%) (Cal. T375)	Thickness (ft)	Design Thickness (ft)
AR-2000 (Control)	NB Lane	2.45	2.31	2.27	92.6	7.4	98.3	.14	.15
	SB Lane			2.29	93.5	6.5	99.1	.26	.15
SEA 20%	NB Lane	2.46	2.33	2.30	93.5	6.5	98.7	.18	.15
	SB Lane			2.29	93.1	6.9	98.3	.24	.15
SEA 40%	NB Lane	2.44	2.31	2.31	94.7	5.3	100.0	.16	.15
	SB Lane			2.31	94.7	5.3	100.0	.26	.15

* Results are average of two core sets per lane.
** Based on density of compacted windrow sample used for stability (Calif. Test 366) test.

The 4-inch cores were tested undisturbed except that the portion below the test section was removed by sawing prior to whole core testing. The portion below the test section was removed from the two 12-inch cores. After combining and thoroughly mixing the remaining material, the mix was apportioned for extraction and grading tests as well as for Abson recovery. Tables 12 and 13 present test data from the 4-inch cores. The tests are basically the same as those presented on Table 5. Generally, the test results on the cores show that all three sections have similar mix properties. Tables 4 and 14 compare favorably to each other regarding the extractions, gradings, and asphalt content results of the new mix and the mix recovered from the 11-month old cores (portions of the combined 12-inch cores). Tables 15 and 16 present the results of tests performed on the binder recovered by the Abson recovery procedure (California Test 380) on portions of the combined 12-inch cores. The 11-month results show that minor hardening of the binder has occurred in each section.

A comparison of relative compaction results shown on Table 12 with the relative compaction results shown in the text (II - Paving Operations) indicates an approximately three percent difference in relative compaction as determined from densities obtained with the nuclear gage and densities obtained from cores. Typically, there is a difference because of the degree of pavement texture influences the nuclear gage determination.

Also presented on Table 16 and Table 17 are microviscosity and microductility data determined from residue obtained by the microrecovery process (California Test 365). The results presented on Table 17 show that the binders used in each section are hardening faster at the surface than deeper in the pavement. This pattern corresponds with previous determinations of hardening with depth.[1]

TABLE 13

PHYSICAL TEST DATA ON 4-INCH CORE SAMPLES
(Cored 10 Months After Construction*)

Test Section	Lane	Sample No.	Stability (Cal. T366) As Received	Stability (Cal. T366) After MVS**	Cohesion (Cal. T306) As Received	Specific Gravity (Cal. T308) Waxed	Specific Gravity (Cal. T308) After MVS**	M_R (ASTM-D4123-82) psix10^5	Surface Abrasion (Cal. T360) Grams Loss Meth. B	MVS** (Cal. T307) % Moisture Absorbed
AR-2000 Control	NB	852-89	26	25	151	2.28	2.27	4.65	17.5	0.40
	NB	852-90	38	33	157	2.27	2.27	4.68	22.2	0.30
	Average NB		32	29	154	2.27	2.27	4.67	19.8	0.35
	SB	852-91	24	26	162	2.27	2.27	4.12	23.3	0.30
	SB	852-92	42	38	154	2.31	2.29	4.53	16.0	0.40
	Average SB		33	32	158	2.29	2.28	4.32	19.6	0.35
SEA 20%	NB	852-87	30	26	161	2.30	2.27	4.53	25.2	0.70
	NB	852-88	29	29	139	2.30	2.30	4.20	26.4	0.60
	Average NB		30	28	150	2.30	2.28	4.36	25.8	0.65
	SB	852-93	29	27	138	2.26	2.26	4.44	27.6	0.40
	SB	852-94	26	31	147	2.32	2.31	4.06	25.6	0.30
	Average SB		28	29	143	2.29	2.28	4.25	26.6	0.35
SEA 40%	NB	852-85	31	34	199	2.31	2.30	4.25	29.4	0.40
	NB	852-86	30	32	192	2.30	2.30	4.88	26.6	0.50
	Average NB		31	33	196	2.31	2.30	4.56	28.0	0.45
	SB	852-95	35	33	248	2.33	2.33	4.95	27.4	0.10
	SB	852-96	40	39	186	2.30	2.32	4.34	26.8	0.20
	Average SB		38	36	217	2.31	2.32	4.64	27.1	0.15

* All cores tested as received.
** Moisture Vapor Susceptibility (MVS)

TABLE 14

EXTRACTION TEST DATA FROM CORES*
(11th Month Cores)

Sieve Size	Spec	Grading Results (% passing) AR-2000 NB Lane	AR-2000 SB Lane	SEA 20% NB Lane	SEA 20% SB Lane	SEA 40% NB Lane	SEA 40% SB Lane
3/4"	100	100	100	100	100	100	100
1/2"	95-100	96	95	97	97	97	97
3/8"	75-90	85	84	82	81	84	84
#4	50-66	63	66	56	56	53	56
#8	35-50	44	46	43	41	38	42
#16		31	32	32	30	28	30
#30	15-30	21	23	22	22	20	21
#50		15	15	15	14	13	13
#100		10	10	9	9	7	8
#200	3-7	7.2	6.5	6.3	5.9	5.0	5.4
Binder Average %/lane		5.5	5.7	5.9	5.6	7.1	7.5
	Average %	5.6		5.7		7.3	

* Extraction Test (Calif. Test 310) on broken up 12-inch cores.

**Lane results average of two core sites.

TABLE 15

RECOVERED BINDER DATA FROM CORES*

Test Section	Lane	Sample No.	Absolute Viscosity at 140°F (AASHTO-T202) (poise)	Kinematic Viscosity at 275°F (AASHTO-T201) (cSt)	Penetration at 77°F (AASHTO-T49) (dmm)	Softening Point (AASHTO-T49) (°F)	Ductility at 77°F, 5cm/min. (AASHTO-T51) (cm)
AR-2000	NB	852-89	4262	425	32	130	100+
(Control)		852-90	5434	465	28	133	100+
		(Average)	(4848)	(443)	(30)	(131)	(100+)
	SB	852-91	5415	441	26	133	100+
		852-92	4990	440	28	134	100+
		(Average)	(5202)	(440)	(27)	(133)	(100+)
SEA 20%	NB	852-87	2956	223	40	129	100+
		852-88	2594	206	40	126	85
		(Average)	(2775)	(214)	(40)	(127)	(92)
	SB	852-93	3299	251	38	129	67
		852-94	2443	210	44	127	100+
		(Average)	(2871)	(230)	(41)	(128)	(83)
SEA 40%	NB	852-85	3049	211	38	128	100+
		852-86	2577	202	41	127	100+
		(Average)	(2813)	(207)	(39)	(127)	(100+)
	SB	852-95	1910	185	48	126	86
		852-96	2500	192	40	129	78
		(Average)	(2205)	(189)	(44)	(127)	(82)

*On residue from Abson recovery (California Test 380) on 12-inch cores. Cores removed 11 months after construction.

TABLE 16

RECOVERED BINDER DATA COMPARISON*

Test Section	Lane No.	Sample No.	On Micro-Recovery Residue** (Cal. T365) Micro-Viscosity at 77°F (megapoise) (Cal. T348) at $0.05s^{-1}$	at $0.001s^{-1}$	Shear Susceptibility (Cal. T348) (Slope)	Micro-Ductility at 77°F (Cal. T349) (mm)	On Abson Recovery Residue (Cal. T380) Micro-Viscosity at 77°F (megapoise) (Cal. T348) at $0.05s^{-1}$	at $0.001s^{-1}$	Shear Susceptibility (Cal. T348) (Slope)	Micro-Ductility at 77°F (Cal. T349) (mm)
AR-2000 Control	NB	852-89	17.6	25.4	.10	27	11.8	12.1	.01	46
		852-90	20.4	25.3	.07	28	16.5	22.6	.08	26
		Average	19.0	25.3	.08	27	14.1	17.3	.04	36
	SB	852-91	17.0	22.7	.08	34	15.7	18.3	.04	32
		852-92	15.8	21.1	.08	4	15.7	20.8	.07	46
		Average	16.4	21.9	.08	19	15.7	19.5	.05	39
SEA 20%	NB	852-87	27.2	62.0	.22	10	16.8	34.5	.19	11
		852-88	22.1	39.0	.15	10	20.0	36.0	.15	17
		Average	24.6	50.5	.18	10	18.4	35.2	.17	14
	SB	852-93	32.0	49.0	.11	14	27.5	74.0	.26	14
		852-94	19.0	36.0	.17	12	20.8	36.0	.14	14
		Average	25.5	42.5	.14	13	24.1	55.0	.20	14
SEA 40%	NB	852-85	23.0	69.0	.28	7	26.0	48.0	.16	15
		852-86	20.3	73.0	.33	3	23.0	42.8	.16	13
		Average	21.6	71.0	.30	5	24.5	45.4	.16	14
	SB	852-95	18.8	47.5	.24	3	14.8	28.1	.17	18
		852-96	21.0	72.0	.32	11	26.7	38.0	.10	23
		Average	19.9	59.7	.28	7	20.7	33.0	.13	20

*Data on residue from cores taken 11 months after construction.

TABLE 17

MICRO-RECOVERED BINDER DATA FROM SLICES (CALIFORNIA TEST 365*)

			Slice 1 - 0 to 1/2" average				Slice 2 - 5/8" to 1-1/8" average				Slice 3 - 1-1/4" to 1-7/8" average				Slice 4 - 2" to 2-3/4" average**			
			Micro-Viscosity (megapoise)		Shear	Micro-	Micro-Viscosity (megapoise)		Shear	Micro-	Micro-Viscosity (megapoise)		Shear	Micro-	Micro-Viscosity (megapoise)		Shear	Micro-
Test Section	Sample Number	Lane	at 0.05 sec^{-1} Shear rate	at 0.001sec^{-1} Shear rate	Suscep-tibility (Slope)	Ductility at 77°F (mm)	at 0.05 sec^{-1} Shear rate	at 0.001sec^{-1} Shear rate	Suscep-tibility (Slope)	Ductility at 77°F (mm)	at 0.05sec^{-1} Shear rate	at 0.001sec^{-1} Shear rate	Suscep-tibility (Slope)	Ductility at 77°F (mm)	at 0.05 sec^{-1} Shear rate	at 0.001sec^{-1} Shear rate	Suscep-tibility (Slope)	Ductility at 77°F (mm)
Calif. Test No.			348		348	349	348		348	349	349		348	349	348		348	349
AR-2000 Control	852-89	NB	25.8	48.0	.16	3	19.6	22.7	.04	18	19.0	23.0	.05	6				
	852-90	NB	24.3	37.5	.11	14	15.8	24.0	.11	21	23.0	34.5	.11	8				
	Average	NB	25.0	42.7	.14	8	17.7	23.3	.08	19	21.0	28.7	.08	7				
	852-91	SB	22.0	37.2	.14	10	18.4	25.0	.07	24	16.8	25.0	.10	19	15.2	18.4	.06	26
	852-92	SB	17.3	22.6	.07	20	12.2	14.9	.05	20	15.0	17.3	.04	22	24.0	33.5	.09	9
	Average	SB	19.6	29.9	.10	15	15.3	19.9	.06	22	15.9	21.1	.07	20	19.6	25.9	.07	17
SEA 20%	852-87	NB	52.0	103.0	.18	5	30.0	70.5	.22	12	27.0	46.0	.14	6	35.3	60.0	.14	6
	852-88	NB	23.5	42.0	.15	2	21.0	58.0	.26	5	18.8	33.5	.15	5	36.3	83.0	.21	5
	Average	NB	37.7	72.5	.17	3	25.5	64.2	.24	7	22.9	39.7	.15	5	35.8	71.5	.18	5
	852-93	SB	47.0	97.0	.19	3	32.5	60.5	.07	2	26.2	63.5	.23	4	22.8	62.0	.26	3
	852-94	SB	54.0	60.0	.03	3	23.5	46.0	.18	6	24.5	42.5	.14	6	17.7	31.0	.16	8
	Average	SB	50.5	78.5	.11	3	28.0	53.2	.12	4	25.3	53.0	.18	5	20.2	46.5	.21	5
SEA 40%	852-85	NB	29.8	83.0	.26	0	24.3	81.0	.31	7	23.3	79.5	.31	6				
	852-86	NB	29.5	87.5	.28	2	20.6	48.5	.22	4	29.0	126.0	.37	4				
	Average	NB	29.6	85.2	.27	1	22.4	64.7	.27	5	26.1	102.7	.34	5				
	852-95	SB	52.0	87.0	.14	3	42.0	53.0	.06	2	28.8	51.0	.15	4	30.5	50.0	.11	3
	852-96	SB	24.3	91.0	.34	11	15.2	38.0	.21	20	21.6	68.0	.30	5	22.0	55.0	.24	3
	Average	SB	38.1	89.0	.24	7	28.6	45.5	.13	11	25.2	59.5	.22	4	26.2	52.5	.17	3

*Recoveries performed on 1/2 of a 4-inch core which was sliced.
Cores recovered 11 months after construction.

**This slice may be contaminated with lower (older) layers.

COST CONSIDERATIONS

It was brought out in the construction report of the Baker Test Section (1) that for sulfur to be a cost-effective substitute for asphalt it could cost no more than half as much as asphalt. To determine whether that criterion is present in the Benton Test Section, the following data are presented:

Bid Item Prices*

	Winning Bid	Avg. Top 5 Bidders
Aggregate (Type A)	$ 14	$ 18
AR-2000 Asphalt	190	166
Sulfur	200	198

*Bid item prices do not necessarily reflect item cost.

Design and Actual Binder Quantities

		Design		Actual
Control Mix (AR-2000)		5.5% AR-2000		5.2% AR-2000
SEA 20%	6.0% =	1.2% Sulfur	5.7% =	1.1% Sulfur
		4.8% AR-2000		4.6% AR-2000
SEA 40%	7.5% =	3.0% Sulfur	7.4% =	3.0% Sulfur
		4.5% AR-2000		4.4% AR-2000

Mix Cost (per ton)

	Design	Actual
Control (AR-2000)	$23.68	$23.15
SEA 20%	24.68	24.14
SEA 40%	27.50	27.32

Since the data show that the cost of sulfur at the Benton Test Section was higher than the cost of the asphalt, and the resulting mix cost per ton of the SEA was higher, we can conclude that the sulfur was not a cost-effective substitute. It should also be noted that the aggregate cost far outweighs the binder cost in AC mix.

Final cost effectiveness of SEA pavements will need to include its service life potential. So far, this has not been determined.

REFERENCES

1. Predoehl, N. H. and Kemp, G. R., "The Construction and Initial Evaluation of Sulfur Extended Asphalt (SEA) Pavement in a Hot Climate (Interim Report 1)", FHWA/CA/TL-86/05, January 1986.

2. Kennepohl, G. J. A.; Logan, A., and Bean, D. C., "Conventional Paving Mixes with Sulfur-Asphalt Binders", Proceedings of the Association of Asphalt Paving Technologists, Volume 44, p. 491., 1975.